

## VIBRATION CONTROL SYSTEM

1

2

3 The present invention relates to improvements in or  
4 relating to vibration control, and in particular to a  
5 variable damper, a vibration control system incorporating  
6 a variable damper and to a method of variably damping  
7 relative motion between two members.

8

9 There are many situations where it is desirable to  
10 control or damp the motion between two objects. One way  
11 of doing so is to use a magnetorheological device, as  
12 described for example in US 2,575,360. Magnetorheological  
13 fluid (MRF) contains a suspension of paramagnetic  
14 particles, such that when a magnetic field is applied,  
15 the particles align with the field thus effectively  
16 increasing the viscosity of the fluid.

17

18 A magnetorheological device typically contains an  
19 electromagnet which generates a magnetic field when  
20 current is passed through its coil. One moving part can  
21 be enclosed within an MRF chamber such that when the  
22 magnetic field is applied, there is opposition to

1 relative motion of that moving part with another moving  
2 part.

3  
4 US 5,492,312 describes a magnetorheological device  
5 wherein a bolt and baffle plate assembly is contained  
6 within an MRF chamber, the fluid in which can have a  
7 magnetic field applied to oppose relative motion between  
8 the assembly and an outer housing, thus damping motion in  
9 up to six degrees of freedom. An electromagnetic coil is  
10 formed around the outer periphery of the device.

11  
12 However, design considerations have thus far limited the  
13 application of magnetorheological devices for use in  
14 devices where the forces that need to be controlled are  
15 relatively high. For a device to support applications  
16 such as those identified, the off-state force, namely the  
17 minimum force required to induce relative motion between  
18 the movable parts, needs to be low. This is difficult to  
19 keep low because of the high density of the MRF, which  
20 can only be reduced at the expense of its damping  
21 effectiveness when a magnetic field is applied.

22  
23 Furthermore an electromagnet can be variably controlled  
24 such that the magnetorheological device provides varying  
25 levels of damping. However, for such control to be  
26 properly refined, there is a requirement that the forces  
27 that would be expected to be applied to the device in use  
28 fall within the force bandwidth, namely the off-state  
29 force and the opposition force provided when the  
30 electromagnet is fully activated.

31

1 It is an object of at least one embodiment of the present  
2 invention to provide a variable damper having a low or  
3 minimal off-state force.

4

5 It is a further object of at least one embodiment of the  
6 present invention to provide a vibration control system  
7 with improved damping.

8

9 According to a first aspect of the present invention,  
10 there is provided a variable damper comprising;

11 an outer member including a magnetically conductive  
12 sleeve;

13 an inner member comprising a shaft;

14 an electromagnet supported between the members;

15 wherein

16 a chamber between the outer and inner members is at  
17 least partially filled with magnetorheological fluid  
18 (MRF), such that when a magnetic field is applied to the  
19 chamber, the effective viscosity of the fluid increases  
20 such that relative motion of the inner and outer members  
21 is opposed;

22 the region between the electromagnet and the  
23 sleeve defining a control region in which the magnetic  
24 field is concentrated.

25

26 Preferably the outer member comprises a hollow  
27 cylindrical body having two body end surfaces, each in a  
28 plane perpendicular to the central axis of the shaft and  
29 spaced outwardly from an end of the electromagnet.

30

31 Preferably the sleeve is located against an inner surface  
32 of the outer member providing an inner sleeve surface

1 centred around the axis of the shaft and spaced outwardly  
2 from the electromagnet.

3

4 Preferably, in a rest position in which no magnetic  
5 field is applied, each body end surface is at a first  
6 distance from an end of the electromagnet, and the inner  
7 sleeve surface is at a second distance from the  
8 electromagnet.

9

10 Alternatively the sleeve may have two sleeve end  
11 surfaces, each in a plane perpendicular to the central  
12 axis of the shaft and spaced outwardly from the  
13 electromagnet.

14

15 The first and second distances represent variables that  
16 define the size and shape of the control region. Here,  
17 the distances as measured from the electromagnet are the  
18 distances that are relevant. However, the electromagnet  
19 may be encased within a housing, and the first and second  
20 distances may be more conveniently defined as being the  
21 distances between the housing and the surfaces.

22

23 Preferably, the first and/or second distances can be  
24 minimised in order to reduce at least one degree of  
25 freedom of the relative motion of the inner and outer  
26 members.

27

28 In an embodiment, the electromagnet is supported on the  
29 outer member. Preferably the electromagnet is supported  
30 by a plurality of struts arranged perpendicular to the  
31 shaft. These struts do not interrupt significantly the  
32 flow path for the MRF through the control region. The

1 electromagnet is therefore fixed in relation to the outer  
2 member.

3

4 Bearings may be located between the electromagnet and the  
5 shaft for ease of manufacture these bearings will be  
6 inert.

7

8 In an alternative embodiment, the electromagnet is  
9 supported on the inner member.

10

11 Preferably, the inner member comprises interconnected  
12 first and second shaft portions, the longitudinal axes of  
13 which, when the inner and outer members are in a relative  
14 rest position, define the centre axis of the damper.

15

16 Preferably, a housing comprising the electromagnet is  
17 interposed between the first and second shaft portions.

18

19 Most preferably, a diaphragm seal portion is provided at  
20 each end of the shaft to bound the chamber.

21

22 Preferably, the shaft is magnetically inert. Thus only  
23 the electromagnet and sleeve need be magnetic. This  
24 allows the damper to be made primarily of light weight  
25 materials such as Aluminium and the like. Light weight  
26 materials decrease the off-state force.

27

28 Preferably, the seal portion has an elasticity to allow  
29 the inner member to rotate in planes perpendicular to the  
30 seal portion.

31

32 Optionally, the seal portion has an elasticity to reduce  
33 at least one degree of freedom of the relative motion of

1 the inner and outer members.

2

3 Preferably, the seal portion comprises a sprung collar  
4 and a diaphragm seal.

5 Preferably, the device comprises an elastic end stop to  
6 protect the device from damage induced from vibrations in  
7 the case where the electromagnet fails.

8

9 The outer member may include a secondary housing at a  
10 body end surface. The/each secondary housing may comprise  
11 a hollow cylindrical body including an aperture through  
12 which the shaft extends. Preferably plastic bearings are  
13 located at the/each apertures against the shaft.

14 Preferably also, the/each secondary housing is filled  
15 with a fluid such as air. These secondary housings act as  
16 supports to assist in providing a single axis damper.

17

18 According to a second aspect of the present invention  
19 there is provided a method of variably damping relative  
20 motion between an outer member including a magnetically  
21 conductive sleeve and an inner member, comprising the  
22 steps:

23 (a) supporting an electromagnet between the members  
24 such that a flow path exists between the  
25 electromagnet and the sleeve;

26 (b) placing magnetorheological fluid between the  
27 members;

28 (c) applying a minimal magnetic field to the  
29 electromagnet;

30 (d) concentrating the field in the flow path; and

31 (e) increasing viscosity of the fluid to thereby  
32 oppose relative motion of the membranes and  
33 create damping with minimal off-state.

1 According to a third aspect of the present invention,  
2 there is provided a vibration control system for reducing  
3 vibrations between a first and a second element, a  
4 magnetorheological fluid variable damper being located  
5 between the elements and operated to cause active damping  
6 between the elements, wherein the system has a relative  
7 figure of merit of less than 0.83.

8  
9 The relative figure of merit provides an indication of  
10 the reduction in vibration achieved by the system.

11  
12 Preferably the relative figure of merit is equal to or  
13 less than 0.5.

14  
15 Preferably the magnetorheological fluid variable damper  
16 is according to the first aspect.

17  
18 Preferably the shaft is connected to the first element  
19 and the housing is connected to the second element; and  
20 the system further comprises a spring located between  
21 elements; first and second accelerometers located between  
22 the damper and the respective first and second elements;  
23 and a control unit for inputting accelerometer values and  
24 outputting a small electric current to the electromagnet,  
25 to cause active damping between the first and second  
26 elements.

27  
28 Preferably the spring is a coil spring. Advantageously  
29 the spring is one or more leaf springs. The leaf springs  
30 may be arranged symmetrically around the damper. A 'c'  
31 ring arrangement of one or more layered leaf springs may  
32 be used. Leaf springs provide a controlled damping with



1 a reduction in dimensions of the vibration control  
2 system.

3

4 Alternatively, the inner and outer members of the damper  
5 are configured to be suitable for attachment to  
6 components of each element on a device, such that the  
7 application of relative forces between the elements  
8 results in corresponding forces being applied to the  
9 inner and outer members of the damper.

10

11 Preferably, a parasitic power generator is incorporated  
12 within or on the device to provide the electric current  
13 that drives the electromagnet.

14

15 Preferably the power generator comprises a plurality of  
16 power generating units that are arrayed on the device at  
17 points where concentrated load would be expected to be  
18 applied to the device when it is put to use.

19

20 Preferably, the units comprise piezoceramic material.  
21 Optionally, the units could comprise piezoelectric  
22 unimorph or bimorph material.

23

24 Preferably, the device comprises at least one sensor  
25 that detects a variable, the value of which can be  
26 used to determine a desired amount of electric current to  
27 be applied to the electromagnetic coil.

28

29 The current applied to the coil can be varied in order to  
30 vary the strength of the magnetic field. In turn, the  
31 effective increase in the viscosity of the MRF, and hence  
32 the amount of damping between the inner and outer members  
33 provided by the damper, is dependent on the strength of



1 the magnetic field. Thus, the desired amount of electric  
2 current that is determined when a particular value of the  
3 variable is detected can be representative of the desired  
4 amount of damping that should be applied given that  
5 value.

6

7 Preferably an intelligent control unit (ICU) is provided,  
8 which is capable of receiving input signals from the  
9 sensors and outputting command signals to the damper..

10

11 Preferably, an algorithm is used by ICU to determine  
12 a desired relationship between the input signals and  
13 the command signals.

14

15 Preferably, the device is a snowboard, one of the outer  
16 member and inner member of the damper is attached to the  
17 surface of the board, and the other of the inner member  
18 and outer member is attached to a raised portion formed  
19 on the board.

20

21 Preferably, the centre axis of the device is transversely  
22 oriented with respect to the longitudinal axis of the  
23 board.

24

25 Preferably, the centre axis of the device is parallel  
26 with the longitudinal axis of the board.

27

28 Preferably, a plurality of dampers are attached to the  
29 board. Dampers may be provided which have a mixture of  
30 centre axis orientations as above.

31

1 Preferably, torsion forks are provided on the board and  
2 connected to the inner member of the device to enable  
3 control of torsional stiffness of the board.

4

5 Preferably, a piezoceramic power generating unit is  
6 provided at a binding assembly.

7

8 The binding assembly is the point at which a boarder  
9 would clip their boots into the board.

10

11 Optionally, the device is a golf club, one of the outer  
12 member and inner member of the damper is attached to the  
13 shaft of the club, and the other of the inner member and  
14 outer member is attached to or forms the grip of the  
15 club.

16

17 Optionally, the device is a handle which is a component  
18 of a machine.

19

20 Such a "machine" may include, for example, a tennis  
21 racket, polo mallet or other sports implement, or may be  
22 a household tool such as a power drill, or may be a  
23 bicycle or motorcycle, with the device being the  
24 handlebar.

25

26 Optionally, the device is an engine mount, or pump mount.  
27 Such devices are found in pumps, generators, engines,  
28 vehicles and the like.

29

30 Embodiments of the present invention will now be  
31 described, by way of example only, with reference to the  
32 accompanying drawings, in which:

33

1 Figure 1 is an isometric view of a variable damper in  
2 accordance with a first embodiment of the present  
3 invention;

4

5 Figure 2 shows an isometric section of the damper shown  
6 in Figure 1 illustrating the struts supporting the  
7 electromagnet;

8

9 Figure 3 shows a sectional view of a variable damper in  
10 accordance with a second embodiment of the present  
11 invention;

12

13 Figure 4 shows a vibration control system according to an  
14 embodiment of the present invention;

15

16 Figure 5 illustrates response curves for a vibration  
17 control system with (a) a theoretical curve of  
18 transmissibility against frequency, (b) an experimental  
19 curve of transmissibility against frequency and (c) a  
20 difference curve from which the relative figure of merit  
21 for a system is derived.

22

23 Figure 6 shows a vibration control system according to a  
24 further embodiment of the present invention;

25

26 Figures 7(a) - (d) show spring arrangements suitable for  
27 use on a vibration control system according to an  
28 embodiment of the present invention;

29

30 Figure 8 shows a snowboard incorporating two variable  
31 dampers, according to an embodiment of the present  
32 invention.

33

1 Figure 9 shows a partial cross sectional view of a  
2 variable damper in accordance with a third embodiment of  
3 the present invention, mounted longitudinally on a  
4 snowboard;

5

6 Figure 10 shows a control schematic for the damper as  
7 illustrated in Figure 9; and

8

9 Figure 11 illustrates a fourth embodiment of a variable  
10 damper, as applied for use with a golf club.

11

12 Referring initially to Figure 1 of the drawings, there is  
13 illustrated a variable damper, generally indicated by  
14 reference numeral 10, according to a first embodiment of  
15 the present invention. Damper 10 comprises an outer  
16 cylinder 12 and an inner shaft 14. The inner shaft runs  
17 symmetrically through the outer cylinder 12. Located  
18 within the outer cylinder, against its inner surface 13  
19 there is a sleeve 15. Steel sleeve 15 provides a magnetic  
20 flux return guide within the damper 10.

21

22 Located within the steel sleeve 15 but independent of the  
23 sleeve and of the shaft 14 is electromagnet 20.

24 Electromagnet 20 has a core 21 surrounded by a mount or  
25 housing 23, which is magnetically inert. The core housing  
26 23 is supported within the region between the shaft 14  
27 and the sleeve 15 by mounts (not shown) onto the outer  
28 cylinder 12. Thus a gap or flow path 25 exists between  
29 the shaft 14 and the housing 23, and a flow path 27  
30 exists between the core 21 and the sleeve 15.

31

32 The outer cylinder 12 defines a chamber 29 located  
33 therein which is bounded at an upper 31 and a lower 33

1 end by diaphragm seals 35 (only one is shown at the lower  
2 end 33). Each diaphragm seal 35 provides a solid collar  
3 around the input shaft 14 which extends from the chamber  
4 through the diaphragms 35 at either end. It is noted that  
5 the shaft 14 is not connected to the EM core 21 although  
6 in further embodiments it may be guided with respect to  
7 the core, by the incorporation of bearings.

8

9 In this embodiment of the present invention, in which  
10 diaphragm seals are provided as part of a piston. The  
11 seals are connected by the input shaft which runs through  
12 the electromagnet.

13

14 In use, a control volume 27 of MR fluid is constant  
15 between the fixed electromagnet (EM) core 21 and the  
16 magnetic flux return guide, sleeve 15. The electromagnet  
17 20 is fixed inside the outer cylinder 12 - mounted inside  
18 the steel sleeve 15 that acts as the magnetic flux return  
19 guide. The input shaft 14 for connection to the vibration  
20 source runs through the centre of the EM core 21, with  
21 opposing diaphragms 35 connected to the shaft 14 and  
22 sealing the system 10. Movement of the input shaft 14  
23 relative to a fixed outer cylinder 12 (connected to the  
24 structure to be damped against) results in a pressure  
25 change in the MR fluid chamber 29 - driving the fluid  
26 around the fixed EM core 20, in the annular orifice 27  
27 between the core 20 and the sleeve 15.

28

29 Activation of the electromagnet 20 controls the flow of  
30 the MR fluid around the electromagnet 20. Increasing  
31 power to the electromagnet 20 results in an increase in  
32 apparent viscosity of the MR fluid between the EM core 21  
33 and sleeve 15. Exposing the control volume 27 of MR fluid

1 to a variable strength magnetic field enables the control  
2 volume 27 to act as a flow control valve. Increasing  
3 resistance to fluid flow enables the device to absorb  
4 more energy from vibration induced movement of the input  
5 shaft 14 relative to the outer cylinder 12.

6  
7 Connecting the input shaft 14 to opposing diaphragms 35  
8 (with a solid collar around the input shaft 14 at either  
9 end, to act as a piston) ensures pressure induced by  
10 movement of the input shaft 14 is equal in both  
11 directions (i.e., up and down when considering figure 1).

12  
13 The movement of fluid from regions experiencing  
14 relatively small magnetic field into the control region  
15 27 helps to reduce degradation in the performance of the  
16 fluid (i.e., as a result of in-use-thickening).

17  
18 One primary and two secondary degrees of freedom can  
19 be controlled with the connected diaphragm actuator 10.  
20 The primary degree of freedom is with the input shaft 14  
21 reciprocating relative to the outer cylinder 12 (i.e., up  
22 and down when considering figure 1). Additionally, pitch  
23 and yaw about the common central axis of this axis-  
24 symmetric actuator can be controlled (i.e., limited  
25 rotational movement about two axes orthogonal to the  
26 common central axis). This is largely possible due to  
27 specification of a diaphragm seal 35, which is a  
28 fundamental part of the piston that induces pressure  
29 driven flow of the MR fluid around the EM core 20.

30  
31 The input shaft 14 runs through the electromagnet core  
32 21, but is not connected to it. To achieve control in  
33 three degrees of freedom the input shaft is machined from



1 a magnetically inert material, so that its movement is  
2 not influenced by the electromagnet.

3

4 Control of movement of the input shaft 14 relative to the  
5 outer cylinder may be advantageous. This can be achieved  
6 by guiding the input shaft through the EM core. A sprung  
7 collar/bush between the outside diameter of the input  
8 shaft and the inside diameter of the EM core can be  
9 specified to control movement of the input shaft against  
10 the EM core (i.e., lateral movement when considering  
11 figure 1).

12

13 Additionally, damper mounts located outside on the outer  
14 cylinder may be made from rubber and specified to act as  
15 an end-stop to prevent movement of the structure  
16 connected to the input shaft against the structure to  
17 which the outer cylinder is fixed. Therefore, rubber  
18 damper mounts around the outer cylinder can act as a  
19 mechanical failsafe, should the electromagnet fail. Due  
20 to the damage that may be caused should a vibration  
21 control system fail, such a mechanical failsafe should be  
22 considered a necessity in a number of applications of the  
23 device.

24

25 By providing a magnetic field across only a small region  
26 27 of the chamber 29, the damper can be operated from a  
27 low off-state. This off-state may be typically 10-20N.

28

29 Figure 2 illustrates the damper of Figure 1 showing the  
30 support means 41 used to locate the electromagnet 20  
31 between the shaft 14 and the cylinder 12. The support  
32 means comprises longitudinally arranged struts 41 which  
33 connect the cylinder 12 to the housing 23 of the



1 electromagnet 20. These struts 41 merely provide support  
2 and do not interrupt MR fluid flow through the region 27  
3 or the return magnetic flux path.

4

5 A yet further feature of the damper 10 is illustrated in  
6 Figure 2. In this embodiment, the housing or outer  
7 cylinder 12 is extended at each end 31,33 respectively to  
8 provide additional supports 43,45. Upper support 43 is a  
9 thickening of the end face of the cylinder 12 and is  
10 located over the diaphragm seal 35. Thus MR fluid in the  
11 chamber 29 is held in, initially by the seal 35 acting on  
12 the piston washer 47, and further by the bearing 49 on  
13 the support 43. The bearing 49 is plastic and provides a  
14 sliding fit against the shaft 14. An identical  
15 arrangement is symmetrically arranged at the lower end 33  
16 of the cylinder 12.

17

18 Figure 2 also shows an additional feature which may be  
19 incorporated into the damper 10. Airflow channels 37 are  
20 machined through the outer cylinder 12 to provide a  
21 coolant flow path through the damper 10. In the  
22 illustration there are four channels 37 shown, however it  
23 will be appreciated that any number can be used, space  
24 permitting.

25

26 The additional supports 43,45 force the damper 10 to  
27 operate on a single axis ie the shaft 14 can only  
28 reciprocate on the central axis through the damper 10.  
29 This restricted movement of the shaft 14 provides the  
30 damper with a low off-state when coupled with the short  
31 control region 27.

32

33 Reference is now made to Figure 3 of the drawings which

1 illustrates a second embodiment of the present invention.  
2 Like parts of those of Figures 1 and 2 have typically  
3 been given the same reference numeral with the addition  
4 of 100. The variable damper (also called an "actuator" or  
5 an "MRF device ") 110 comprises an outer portion 112 and  
6 an inner portion 114. The inner portion 14 comprises a  
7 first portion 116, second portion 118, and an  
8 electromagnet 120. Power lines 122 are provided within  
9 the first portion 116 to power the coil 124 of the  
10 electromagnet 120.

11  
12 The first 116 and second 118 portions have seals 115,  
13 which, together with an inner surface of the outer  
14 portion 112 define an MRF chamber 128. When electric  
15 current flows through the electromagnet coil 124, a  
16 magnetic field 128 is induced, which has the effect of  
17 increasing the effective viscosity of the MRF in the  
18 chamber 128, the increase being dependent on the  
19 power of current being passed through the coil 124.

20  
21 Inner seals 115 and outer seals 117 together define the  
22 seal portion of the inner member 14. Any suitable form of  
23 seal may be used, suitably a diaphragm grommet seal.  
24 Additionally the seal portion could be provided by a  
25 sprung collar and diaphragm seal at opposite ends of the  
26 inner portion, in a similar arrangement to the diaphragm  
27 seal 35 and washer 49 of Figure 2.

28  
29 Insertion of a sprung collar between the inner axle 114  
30 and outer cylinder 112 provides resistance to movement,  
31 proportional to the stiffness of the spring in a  
32 particular axis. The MR fluid, electromagnet and sleeve  
33 (or cylinder) adds control of dynamic movement.

1 The sprung collar provides primary control in two axes  
2 orthogonal to the central axis and secondary control  
3 along the central axis.

4

5 In an alternative embodiment, the sprung collar may be  
6 replaced by a sprung bush, as is known in the art.

7

8 In further alternative embodiments which are not  
9 illustrated herein, the sprung collar may have a  
10 rectangular or square cross-section.

11

12 The incorporation of sprung collars or bushes between the  
13 inner axle and outer cylinder has a number of benefits in  
14 many applications, including;

15

16 1. To resist deflection of the inner relative to the  
17 outer up to a specified off state force.

18

19 2. To return the inner and outer to their neutral, rest  
20 separation.

21

22 3. To ensure the inner and outer do not actually touch.

23

24 4. To control axial movement.

25

26 Items 1 and 3 are conflicting requirements, so therefore,  
27 a mechanical end-stop may be additionally specified (to  
28 prevent the inner touching the outer), should it not be  
29 possible with the same spring to provide a low off state  
30 force and ensure clearance is maintained.

31

32 The spring constant does not necessarily have to be equal  
33 at either end of the cylinder. This presents the

1 opportunity to control axial movement, with resistance to  
2 movement (between the inner axle and outer cylinder) at  
3 one end of the MRF device being greater or less than the  
4 resistance at the other end.

5

6 The damper 110 operates in a similar manner to damper 10.  
7 Controlling the viscosity of the MRF means that the  
8 damping of relative motion between inner and outer  
9 portions 12, 14 can be controlled.

10

11 A steel (or other magnetically conductive material)  
12 sleeve 130 is mounted internally in the outer portion  
13 112, which provides a flux return path through the  
14 electromagnet 120 for the magnetic field. This has the  
15 effect of concentrating the magnetic field in a region  
16 132 between the inner and outer portions 112, 114,  
17 defining a control volume of MRF within the chamber 128  
18 that acts as a control region. It is the variation of the  
19 viscosity of this control volume that is critical to  
20 controlling the damping. MRF in the remaining volume of  
21 the chamber 128 is not activated by the magnetic field  
22 when it is applied.

23

24 The chamber 128 is bounded by the outer member 112,  
25 rather than the sleeve 130. Thus, the volume of the MRF  
26 in the device is larger than the control volume.

27

28 This ensures that fluid in the control volume can be  
29 recycled with fresh fluid as the inner member 114 is  
30 moved relative to the outer member 112, the MRF in the  
31 control volume being moveable away from the electromagnet  
32 to a region of the MRF chamber that is substantially  
33 outside the magnetic field. This re-circulation of the

1 fluid reduces the likelihood of fluid-particle separation  
2 and in-use thickening, to improve the longevity of the  
3 device.

4

5 The housing that includes the sleeve 130 can be made from  
6 a single component, where the outer housing is made from  
7 steel and provides the field return path or up to three  
8 components, where the steel sleeve 30 is assembled  
9 between split cylinder that makes the outer housing.

10

11 This simple construction reduces the number of moving  
12 components, making the damper 110 easy to manufacture,  
13 and also making it durable.

14

15 The electromagnet 120 comprises copper wire wound around  
16 a steel core mounted on an inner axle. Therefore, the  
17 magnetic flux generator is axis-symmetrically mounted  
18 with the MR fluid between it and an outer cylinder to  
19 which a steel (or other magnetically conducting material)  
20 cylinder is internally mounted - providing a flux return  
21 path (to the electromagnet, through the MR fluid).

22

23 Mounting the electromagnet on the axle has been  
24 considered the most power efficient means of generating  
25 magnetic field in the system. Prior devices, in which a  
26 coil is wound around the outer cylinder with a  
27 magnetically conductive piston mounted on the axle to  
28 complete the magnetic circuit, require considerably more  
29 power in order to generate a comparable magnetic field  
30 with the device thus constructed. However, the  
31 arrangement of the electromagnet independently suspended  
32 between the axle and the outer cylinder, providing a  
33 control region between the electromagnet and the outer

1 cylinder, has been found by the inventors to give a more  
2 power efficient means and thus a damper with the lowest  
3 possible off-state force. This is the embodiment shown in  
4 Figures 1 and 2.

5  
6 The advantage of the embodiment shown in Figure 3 is that  
7 it provides for multi-axis control. Two translational  
8 degrees of freedom are provided, as the inner portion 114  
9 translates in a direction along an axis running from left  
10 to right of the device 110, or in a direction along an  
11 axis extending normal to the page, as illustrated in  
12 Figure 3.

13  
14 When a magnetic field is applied, the resistance to this  
15 relative translational motion that is provided by the MRF  
16 is known as a pressure driven flow mode.

17  
18 Activation of an electromagnet produces an apparent  
19 change in viscosity in MRF exposed to the generated  
20 magnetic field. As the MR fluid becomes more viscous,  
21 more force is required to generate a pressure that causes  
22 the fluid to flow around a constriction. The movement of  
23 the electromagnet on the inner axle relative to the outer  
24 steel sleeve creates a constriction and (pressure driven)  
25 fluid flow can be controlled (like a valve) as the  
26 electromagnet activates the MR fluid.

27  
28 There is also a rotational degree of freedom for relative  
29 rotation about a central axis 134 of the device 110.

30  
31 When the two portions 112, 114 attempt to rotate relative  
32 to each other in this way, the MRF resists the movement  
33 by a shear force that is induced at the surfaces of the



1 chamber 128. This can be known as the direct shear mode of  
2 damping control. The strength of resistance to motion  
3 offered by the direct shear mode is much less than the  
4 strength offered by the pressure driven flow mode.

5  
6 The inner member 114 comprises a first portion 16, a  
7 second portion 118, and a housing containing the  
8 electromagnet 120. These portions are integral, and the  
9 longitudinal axes of the first and second portions are  
10 in-line and define a central axis 34 both of the inner  
11 member 114 and the device 10.

12  
13 Seals 115, 117 provide sufficient elasticity for the  
14 shaft of the inner member to rotate about an axis running  
15 into and out of the page of the device as illustrated in  
16 Figure 3 (i.e. moving clockwise/anticlockwise in the  
17 figure), and about an axis running from left to right  
18 horizontally as illustrated in Figure 3 (i.e. tilting  
19 into and out of the page in the figure).

20  
21 Movement between the inner 114 and outer 116 portions in  
22 a direction along the central axis 134 of the device is  
23 limited in its extent by the seals.

24  
25 Spring return to the neutral position results from the  
26 viscoelastic property of the seals / with sprung collars  
27 located between seals, against the inner and outer (i.e.,  
28 in the space between the shaft and the outer housing).  
29 Thus, the two translations at right angles to the shared  
30 central axis (of the inner axle and outer cylinder), plus  
31 pitch and yaw about the same axis can be considered as  
32 being four primary degrees of freedom that can be  
33 controlled, while one translation of the inner member



1 relative to the outer member along the shared axis and  
2 one rotation about the same axis (assuming the diaphragm  
3 seal is assembled to rotate with the inner axle) can be  
4 considered as two secondary degree of freedom can be  
5 controlled. The secondary degrees of freedom are limited  
6 by the seals.

7

8 One advantage of the damper described above lies in its  
9 ability to provide control of dynamic movement over a  
10 range (i.e. a control bandwidth). The control bandwidth  
11 is between the off state (no power to the electromagnet;  
12 fluid not activated) and the on state (electromagnet  
13 fully on; fluid fully activated).

14

15 It is important that off-state force is sufficiently low  
16 for the control bandwidth of the MRF device to act over  
17 the operating range of the product to which it is fitted.  
18 Should the off-state force (required to move the MRF  
19 device) be outside or near the upper limit of the  
20 operating range, the control bandwidth of the MRF device  
21 is of little benefit to the product to which it is  
22 fitted, and a passive vibration control solution would be  
23 better considered.

24

25 A low off state force capability can be achieved by:

26

- 27 1. Reducing the viscosity of the MR fluid, while avoiding  
28 significant reduction in the % volume of carbonyl iron  
29 content (that would reduce the on state capability).
- 30 2. Increasing the gap between the electromagnet and the  
31 steel sleeve / cylinder, without increasing the gap to  
32 an extent that the magnetic field strength (generated

1 with the electromagnet activated) becomes dissipated -  
2 i.e., reducing the on state capability.

3 3. Specifying seals with sufficient elasticity to  
4 maintain the MR fluid stays in the outer cylinder, but  
5 avoids significant energy being absorbed by the seals  
6 as the inner is forced to move relative to the outer.

7  
8 The MRF dampers 10,110 of the present invention operate  
9 with a low viscosity fluid to ensure a low off state  
10 force is maintained. Concerns with settling and in-use-  
11 thickening (where the activated MR fluid degrades to a  
12 paste-like consistency) are significantly reduced if the  
13 MR fluid in the control volume and particularly the  
14 control region can be re-circulated (i.e., with MR fluid  
15 not exposed to the magnetic field). Spaces are provided  
16 in the chambers 29,128 on either side of the control  
17 region 27,132 for this purpose.

18  
19 The variable dampers of the present invention have a wide  
20 range of applications, and the scope of the invention  
21 should not be construed as being limited to a particular  
22 application. Thus reference is now made to Figure 4 which  
23 illustrates a vibration control system, generally  
24 indicated by reference numeral 50, according to an  
25 embodiment of the present invention.

26  
27 Figure 4 illustrates a standard vibration control system  
28 50, which controls movement between two moving objects 52  
29 and 54. It will be appreciated that one object eg. item  
30 54, may be static and that all movement is upon the first  
31 item 52. Located between the objects 52, 54 is a spring  
32 56. Also located between the two objects is a vibration  
33 damper 210. The housing or outer cylinder 212 of the

1 damper is connected to the first object 54 while the  
2 inner shaft 214 of the damper 210 is connected to the  
3 second object 52.

4  
5 Further, at positions where the dampers meet the object  
6 there is located an accelerometer 58a,b. The  
7 accelerometers 58a,b give an indication of the movement  
8 each of the objects 52, 54. The output of each  
9 accelerometer 58a,b spread to a control unit 60 from  
10 which an electrical signal passes to a damper 210 to  
11 provide the magnetic field on the magnetorheological  
12 fluid within the damper 210. An optimised algorithm is  
13 programmed into the control unit 60 onto a microprocessor  
14 so that the electrical signal to the damper can be varied  
15 in accordance with the values determined from the  
16 accelerometers 58a,b.

17  
18 Damper 210 is as described with reference to Figures 1  
19 and 2. While the control unit 50 could use the second  
20 embodiment shown in Figure 3, the single axis damper of  
21 Figures 1 and 2 is most appropriate. The advantage of  
22 using the active damper of Figures 1 and 2 is that it  
23 provides a low off-state indicated by the  
24 transmissibility against frequency curve obtained. This  
25 is as indicated in Figure 5.

26  
27 Reference is now made to Figure 5(a) of the drawings,  
28 which indicates a theoretical graph showing  
29 transmissibility against frequency. Drawn as a Bode  
30 Magnitude Diagram of magnitude (dB) against frequency  
31 (rad/sec), curve (a) of the graph shows the classic  
32 initial peak and trailing edge normalised characteristic  
33 of the mass 52 supported by the spring 56 alone and

1 having a resonant frequency  $f_n$ . In the same system with a  
 2 fixed damper, curve (b), the peak in transmissibility is  
 3 reduced to near one, however the trailing edge provides a  
 4 higher transmissibility at the high frequencies. The  
 5 active damper 210 provides an optimal curve, curve (c),  
 6 with a low off-state. This curve provides the smoothness  
 7 to the peak with a transmissibility of close to one,  
 8 matching that of the fixed damper. On the trailing edge,  
 9 it has properties close to the ideal properties of the  
 10 spring at the higher frequencies.

11  
 12 Experimental results taken from a sprung mass system  
 13 similar to the theoretical one in Figure 5(a) are plotted  
 14 in Figure 5(b) showing the characteristics of both the  
 15 spring alone, curve (d), and the optimally controlled  
 16 system, curve (e). The relative normalised  
 17 transmissibility improvement using the optimally  
 18 controlled variable damper 212 against the spring only  
 19 system is shown in difference graph of Figure 5(c)  
 20 whereby a positive figure indicates a reduction of  
 21 vibration. A single figure of relative merit of 0.8229  
 22 for this improved system is derived by the ratio of  
 23 integral of transmissibility from 0-100 Hz for the  
 24 controlled damper system over integral of  
 25 transmissibility for the spring only system. The equation  
 26 for this is given:

27

$$\frac{\int_0^{100\text{Hz}} \text{trans}(\text{ControlledDamper})}{\int_0^{100\text{Hz}} \text{trans}(\text{SpringOnly})}$$

29

30 Any comparison to alternative damper designs should be  
 31 evaluated using the baseline of the spring only graph

1 given in Figure 5(b) in order that a fair comparison can  
2 be made. This means that a system with a replica  
3 transmissibility function would need to be used.

4

5 It is estimated that with ongoing refinements to the  
6 system to improve optimisation, this relative figure of  
7 merit can be brought down to 0.5 or better.

8

9 The control system of Figure 4 finds particular  
10 application in respect of engine mounts, pump mounts and  
11 power tools. The engine block could be mounted at the  
12 object marked 52 and thus provides the vibration control  
13 for pumps, generators, engines and in vehicle  
14 manufacture.

15

16 A further embodiment of a vibration control system,  
17 generally indicated by reference numeral 150, is  
18 illustrated in Figure 6. Like parts to those have been  
19 given the same reference numeral with the addition of  
20 100. The system 150 now incorporates a pivot 53. In  
21 this way the load, or first object 152 acts on the damper  
22 212 against the pivot 53. The system 150 may incorporate  
23 accelerometers and a control unit as described with  
24 reference to Figure 4.

25

26 The spring 156 in this embodiment is formed by leaf  
27 springs as distinct from the typical coil spring. These  
28 leaf springs can be advantageously arranged around the  
29 damper 212 to save space and provide better control to  
30 the system 150. A non-exhaustive selection of suitable  
31 arrangements is illustrated in Figures 7(a)-(d). Figure  
32 1(a) illustrates a crossed pair over the damper 212. Each  
33 spring 156 is in a 'c' spring formation with both ends on

1 the second object 154. Figure 7(b) illustrates a triplet  
2 arrangement of three springs, meeting at the first object  
3 152 and distributed across the second object 154. Figure  
4 7(c) provides a quad arrangement of four independent leaf  
5 springs 156(a)-(d) which are symmetrically distributed  
6 around the damper 212. Figure 7(d) illustrates an  
7 arrangement for adjusting the resonant frequency of the  
8 spring 156 by layering individual leaf springs, creating  
9 a progressive type leaf spring. The lowest spring in the  
10 configuration is in a 'c' spring formation with the  
11 additional springs symmetrically aligned on its upper  
12 surface.

13

14 As a particular example, the invention will now be  
15 described as is incorporated in a snowboard.

16

17 This application is shown generally in Figure 8. A board  
18 340 has bindings 342 with shim portions 344, to which the  
19 outer portion 312 of a damper (or "actuator") 310 is  
20 attached. The inner portion 314 of the damper 310 is  
21 attached to the board 340. Torsion forks 346 are also  
22 mounted on the board 340, and are also in communication  
23 with the inner portion 314 of the damper 310. The damper  
24 310 primarily as described herein with reference to  
25 Figure 3.

26

27 As is described in more detail below, sensors monitor  
28 dynamic movement and provide input to an intelligent  
29 control unit (ICU) made up of one or more  
30 microprocessors. The response (i.e., energy absorbing  
31 capability) of the MRF actuator(s) controls dynamic  
32 movement of the product with a view to optimising



1 performance/tuning the system to suit the operator  
2 player).

3

4 The multi-axis damper 310 aims to provide a wide  
5 bandwidth of semi-active damping. The system will enable  
6 the level of vibration energy absorption to be adapted  
7 with respect to vibration impulses (i.e., the product of  
8 force and time) and can be tuned to suit the user.

9

10 Soft flex, torsionally flexible boards are easier to  
11 turn and better to control at lower speeds and are  
12 generally better off piste. Stiff, torsionally rigid  
13 boards have greater stability at speeds and have enhanced  
14 carving ability - making it easier to place the board in  
15 a turn at speed. Damper 310 is capable of adapting the  
16 characteristics of the board with respect to speed and  
17 snow conditions. This is achievable by using integrated  
18 sensors to monitor the amplitude and time response of  
19 vibrations that can be used to characterise speed and  
20 surface condition, with an algorithm programmed into a  
21 microprocessor controlling power supply to the  
22 electromagnets that adapt the energy absorbing capability  
23 of the MRF actuator(s) ie. dampers 310.

24

25 The actuator must be mounted so that torsional and  
26 longitudinal movement of the board can be transmitted  
27 through the actuator.

28

29 For a snowboard, the actuator can be mounted with its  
30 central axis 334 either transverse or parallel ("in-  
31 line") to the longitudinal axis of the board 340.

32



1 Figure 9 shows a third embodiment of the present  
2 invention, namely an actuator 350 that is mounted in line  
3 with the board 340. Components of the actuator 360 are  
4 similar to the components referred to in Figure 3 and  
5 shall not be hereinafter described in detail. The  
6 reference numerals that apply to Figure 3 can be taken to  
7 refer to the corresponding components in Figure 9 now  
8 prefixed '3'.

9  
10 The sprung collar or the bush described with reference to  
11 Figure 3, are not essential parts of the MRF device when  
12 it is incorporated in to a snowboard, as the board acts  
13 as the spring that is to be controlled. MRF devices with  
14 sprung collars or bushes would add to the stiffness  
15 matrix of the board and provide adaptive semi-active  
16 control of dynamic movement. On the snowboard, the  
17 actuator is returned to a neutral position as the board  
18 relaxes after being deflected (assuming the board does  
19 not become permanently deformed).

20  
21 The electromagnet 320 is powered by power supply 352  
22 routed through the shim 344. The MRF chamber 328 is  
23 attached to the board 340, and the outer portion 312 of  
24 the actuator 360 is attached to the shim 344. If the  
25 actuator 360 is transversely mounted, the chamber 328 and  
26 outer portion 312 are connected to the board 340 and shim  
27 344 also.

28  
29 Steel sleeve 354 is attached to the outer cylinder 312 of  
30 the outer member, and has the shape of a cylindrical body  
31 portion with two washer shaped end portions at each end  
32 of the cylinder, the outer edges of which are in line  
33 with the outside perimeter of the body portion. The

1    electromagnet 320 is mounted on an axle and positioned  
2    inside the steel cylinder 354.

3

4    The inner axle and outer cylinder share a common axis.  
5    There is a defined gap between the electromagnet and the  
6    steel cylinder, comprising a first dimension X, being the  
7    distance between the end of the electromagnet 320 and the  
8    inner wall of the steel cylinder 354, and a second  
9    dimension Y, being the distance between the inside  
10   diameter of the steel cylinder 354 and the outside  
11   diameter of the electromagnet 320.

12

13   The gaps as defined by the dimensions X and Y enable  
14   the device to control up to six degrees of freedom.

15

16   To minimise the off state force, X and Y should be made  
17   as large as possible, bearing in mind that their increase  
18   will result in a corresponding decrease in the force that  
19   can be provided by the device once the full on state is  
20   applied.

21

22   As shown in Figure 8, the torsion forks 346 are connected  
23   to the inner portion 314, to transmit longitudinal and  
24   torsional movement to the MRF actuator.

25

26   The MRF actuator 360 can adapt semi-active damping of  
27   torsional and longitudinal movement with a combination of  
28   the pressure driven flow (/ valve mode) and direct shear  
29   mode of the MR fluid being applied.

30

31   Mounted with its axis parallel to the axis of the board,  
32   the MRF actuator can adapt semi-active damping of  
33   longitudinal movement with a combination of the pressure

1 driven flow (/valve mode) and direct shear mode of the MR  
2 fluid being applied. Torsional stiffness can be adapted  
3 by applying the direct shear mode to resist rotation of  
4 the inner relative to the outer.

5

6 Adaptive control of the damping is provided by an  
7 intelligent control system. Figure 10 shows an  
8 intelligent control system 90 suitable for use with the  
9 damper 360 shown in Figure 9. It will be appreciated that  
10 a similar control system would be suitable for a  
11 transversely mounted actuator.

12

13 Integration of a parasitic power generator is preferable  
14 to powering the system from a battery. A piezo-ceramic  
15 power generator 70 (such as PZT - lead zirconium  
16 titanate) located at areas of concentrated load can be  
17 used to harvest power from deflections induced by the  
18 movement between the rider and the board.

19

20 The location of the generator could for example, be  
21 specified to be under the riders boot. For example, the  
22 power generator could be a piezoelectric (lead-zirconium  
23 titanate - PZT) bimorph / piezoelectric (PZT) unimorph  
24 located in the binding foot-plate/ between the binding  
25 assembly and the deck of the board.

26

27 This is in contrast to presently available systems, which  
28 merely use the vibration caused by movement of the board  
29 to generate power. By placing the piezo-ceramic power  
30 generators 70 at strategic points where there is  
31 concentrated load and/or movement from the rider of the  
32 board when using it, enough power can be generated to  
33 power the electromagnet and ICU.

1 The piezo-ceramic generator 70 located within the binding  
2 assembly (/between the binding and board) can power an  
3 energy efficient network of control-actuator(s).  
4

5 An array of piezo (polymer) sensors (e.g.,  
6 polyvinylidenefluoride - PVDF) sensors 72 provides a  
7 self-powered vibration monitoring capability. An array of  
8 sensors 72 located within the beam section to be  
9 controlled can provide input to the control interface on  
10 longitudinal and torsional dynamic movement produced from  
11 surface induced impulses.  
12

13 This system must be sufficiently energy efficient so that  
14 the power available to the electromagnet can sufficiently  
15 change the apparent viscosity of the MR fluid, resulting  
16 in a satisfactory improvement in dynamic control.  
17 Therefore, the number of turns on the core of the  
18 electromagnet must be sufficient to generate a  
19 satisfactory on state. but be conservative in number to  
20 conform to the power constraints. The available energy  
21 and required control bandwidth must be considered for  
22 each application.  
23

24 The data provided by the sensors 72 can be used to  
25 determine the amplitude and frequency characteristics of  
26 board vibration induced as the board 340 moves over the  
27 snow. Characteristics of the vibration can be used to  
28 determine environmental inputs (e.g., hard / soft packed  
29 snow), based on information pre-programmed into the lCU  
30 90.  
31

32 The lCU 90 controls the power supply to the electromagnet  
33 20 such that vibration amplitude and frequency may be

1 controlled subject to the applied control algorithm  
2 (e.g., proportional control/proportional-integral-  
3 differential control/sky-hook algorithm/to a set value -  
4 up to a definable maximum).

5

6 One or more MRF actuators may be mounted transversely, or  
7 with its axis parallel to that of the board as described  
8 above in order to provide multi-axis control.

9

10 Another major application of the present invention is the  
11 incorporation of an actuator in the grip of sports  
12 equipment, such as for example tennis, squash or  
13 badminton rackets; golf clubs; baseball or cricket bats;  
14 or polo mallets.

15

16 Figure 11 shows the application of an adaptive shock  
17 absorbing grips may integrated on a golf club 80.

18

19 The MRF device 110 is integrated so that the axis is in-  
20 line with the axis of the shaft 82, with the inner  
21 component mounted to the shaft 82 and the outer making up  
22 the grip. Activation of the electromagnet mounted on the  
23 structural inner component results in an apparent  
24 viscosity change in the MR fluid between the inner and  
25 outer (grip), reducing relative movement in two axes and  
26 introducing an adaptable energy absorbing capability.

27

28 A spring return to a neutral position is required. Sprung  
29 collars or bushes can be located between the seals  
30 against the inner axle and outer cylinder (i.e. in the  
31 space between the shaft and the outer housing) to provide  
32 resistance to deflection that the MR fluid is able to

1 dynamically control. Therefore the spring is integrated  
2 in the damper assembly.

3

4 A contact plate can interface the shock-absorbing grip  
5 with the sensor-control and power supply elements of the  
6 system.

7

8 For this application, and application to handles of other  
9 devices, it is desirable to actively prevent translation  
10 along and rotation about the shared central axis of the  
11 inner member relative to the outer member, so the off  
12 state force in these degrees of freedom needs to be  
13 raised.

14

15 This is possible by specifying seals with appropriate  
16 elasticity to prevent noticeable movement.

17

18 Again, integration of a parasitic power generator is  
19 preferable to powering the system from a battery. A  
20 piezo-ceramic power generator located at a point of  
21 concentrated load can be used to harvest power from  
22 deflections induced by the movement between the head or  
23 club, the shaft, and the handle (where the grip is  
24 located). The piezo-ceramic generator can power an energy  
25 efficient network of control-actuator(s), with piezo  
26 (polymer) sensors providing self-powered vibration  
27 monitoring capability.

28

29 PVDF sensors are proposed to provide a self-powered  
30 vibration monitoring capability. An array of sensors  
31 located within the shaft can provide input to the control  
32 interface on transmitted vibrations resulting from shock  
33 induced impulses.



1 A further identified application of multi-axis adaptive  
2 semi-active control of dynamic movement is in bicycle and  
3 motorbike handles. Sports bikes with low handles result  
4 in a riding position that puts weight on the rider's  
5 wrists, with fatigue compounded by any shock induced  
6 vibration that is not sufficiently damped by the main  
7 front suspension. One or more multi-axis MRF device can  
8 be located in the bike handles as a secondary system to  
9 absorb shock and reduce wrist fatigue.

10

11 In a motorcycle application there is sufficient capacity  
12 to power the MRF device(s) with negligible performance  
13 consequences.

14

15 Applied to bicycles, although it is possible, it is  
16 advantageous not to power the MRF device(s) from the  
17 powertrain (i.e., rotation of the pedals / the wheels) as  
18 this will reduce performance. An alternative, to a dynamo  
19 powering the MRF device(s) from the powertrain, is a  
20 parasitic power generator - preferably located between  
21 the bicycle and rider, at a position, where there is a  
22 concentrated load.

23

24 A piezo-ceramic power generator located in the seat-post  
25 can be used to harvest power from deflections induced by  
26 the movement of the rider on the seat. The piezo-ceramic  
27 generator can power an energy efficient network of  
28 control-actuator(s), with piezo (polymer) sensors  
29 providing self-powered vibration monitoring capability.

30

31 The single axis damper with additional supports provides  
32 a damper with the lowest possible off-state. When  
33 incorporated in a vibration control system, as could be



1 used on engines, pumps, generators etc, the damper  
2 provides a system with an ideal transmissibility against  
3 frequency curve.

4

5 Improvements and modifications can be made to the above  
6 without departing from the scope of the present  
7 invention. In particular, the application of the  
8 invention to be incorporated in specific devices is not  
9 limited to the list of specific devices herein.

10 Furthermore, it will be apparent that the specific  
11 geometry of, for example, the layout of the sensor array  
12 or of the parasitic power generators may be varied as  
13 appropriate for the specific application being  
14 considered.